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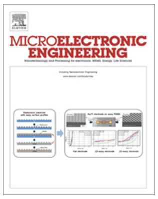

An integrated planar magnetic micropump

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This paper presents an integrated magnetic micropump that uses in-plane compliance-based check valves and a magnetically actuated membrane. The device, which allows for simple fabrication and system integration with other functional elements, consists of two functional layers both fabricated from poly(dimethylsiloxane) (PDMS). The upper PDMS layer provides a compliant membrane with an electroplated thin-film permalloy strip for actuation, while the lower PDMS layer incorporates microfluidic components including the microchannels, pump chamber, and a pair of check valves for flow regulation. The PDMS check valves, each having a compliant flap in contact with a stiff stopper to allow for unidirectional fluid flow with minimized leakage, are located at the inlet and outlet of the pump chamber, respectively. As such, the unidirectional flow at a controlled volumetric rate can be readily generated in accordance with the pumping actions. Systematic characterization of the micropump has been performed by studying the dependence of its pumping flow rate on the driving frequency of magnetic actuation, and the back pressure. Experimental results show that this micropump is capable of generating fluid flow of 0.15 μL/min at the frequency of 2 Hz, corresponding to a volume resolution of 1 nL per stroke, and working reliably against a maximum back-pressure of 550 Pa, demonstrating the potential application of this micropump for various integrated lab-on-a-chip systems.

1. Introduction

Lab-on-a-chip (LOC) microsystems integrate a wide variety of laboratory functions in a single miniaturized device, and offer advantages such as reduced sample consumption, improved system compactness and portability, and low cost. To date, LOC microsystems have been widely pursued for chemical analysis, environmental monitoring, molecular biology and medical investigations [1–4]. In such systems, biochemical solutions must be handled in minute volumes down to nanoliters, and such operations entail integrated micropumps for precise mobilization and control of fluid flow. To this end, a wide variety of micropumps using different fabrication techniques and actuation schemes have been developed [5].

The most commonly used micropumps for LOC systems are membrane-based [6,7] with actuation methods exploiting electrostatic [8,9], piezoelectric [10,11], thermopneumatic [12,13], shape memory alloy (SMA) [14], electromagnetic [15–18], and pneumatic [19,20] effects. In particular, magnetic micropumps hold great potential for fully integrated LOC microsytems with advantages of rapid time response, large displacement, and low actuation voltage. The earliest magnetic micropumps were created by silicon-based micromachining techniques, which are typically complicated and expensive [21]. Alternatively, polymeric materials, such as silicone [18], polycarbonate [22], poly(methyl methacrylate) (PMMA) [23], and poly(dimethylsiloxane) (PDMS) [24], have been used to fabricate magnetic micropumps. However, current polymeric magnetic micropumps mostly exploit hybrid designs involving multilayered structures with out-of-plane flow control elements, which still require complicated fabrication and packaging, and more importantly, difficulties in integration with other functional components. Recently, valveless magnetic micropumps based on nozzles and diffusers have been developed with simple planar design, fabrication, and integration [25–27]. These benefits, however, are accompanied by the lack of self-blocking due to the low diodicity (i.e. the ratio of forward flow rate to reverse flow rate) of the nozzle/diffuser components. Therefore, a back pressure at the outlet, typically existing in practice, may cause reverse fluid leakage, which is undesirable for LOC microsystems as the cross contamination between the upstream and downstream fluids may occur [5].

In contrast, integrated microfluidic systems using planar check-valves for flow regulation [28–30] could potentially address these issues. We have previously used planar check valves to demonstrate a pneumatic micropump [31], although the use of pneumatic

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actuation significantly limited the device's level of integration and portability. Here, we present an integrated micropump combining on-chip, membrane-based magnetic actuation with an electroplated permalloy thin-film strip, and in-plane compliance-based PDMS check valves for fluid regulation. The device is fully integrated in the sense that all microflow control components are integrated in a single layer, and the magnetic component is simply integrated within a thin membrane. As such, this device is miniaturized and allows for simple fabrication and easy integration with other functional elements. Moreover, the device is directly actuated through an externally applied magnetic field, providing an efficient and wireless operation method, desirable for applications to implantable biomedical systems. We have characterized the micropump by systematically studying the pumping flow rate at varying operational parameters such as the driving frequency, magnetic field strength, and back pressure. Experimental results demonstrate that the micropump is able to produce continuous flow with a volume resolution of approximately 1 nL at the frequency of 2 Hz.

2. Design and principle

The micropump mainly comprises two functional layers (Fig. 1a): a compliant PDMS membrane with a thin permalloy strip on top for magnetic actuation, and a lower PDMS functional layer incorporating flow control elements, including planar check valves, a square-shaped pump chamber (4 mm × 4 mm × 160 μm in length, width, and height, respectively), and flow channels ($400 \times 160\ \mu m^2$ in width and height). These two functional layers are then sandwiched between a flat PDMS or glass substrate and a PDMS encapsulation layer that is used to cover the PDMS membrane. The two check valves are placed, respectively, at the inlet and outlet of the pump chamber (called "inlet valve" and "outlet valve") to regulate the flow in a unidirectional manner. The permalloy actuation strip has a dimension of $3000 \times 1740 \times 20\ \mu m^3$ in length, width, and thickness, respectively, and covers one half of the square membrane (4 mm × 4 mm × 20 μm in length, width and thickness), with an edge-to-edge distance of 500 μm from the membrane edges (Fig. 1b).

The check valves in the micropump exploit a simple planar configuration [32] in which a compliant flap ($60 \times 350 \times 160\ \mu m^3$ in length, width, and height, Figure 1c) is as-fabricated in contact with a stiff stopper ($250 \times 340\ \mu m^2$ in length and width). Under forward pressures (from the inlet to the outlet as shown in Fig. 1), the flap is pushed away from the stopper, allowing fluid passage. While under reverse pressures (from the outlet to the inlet), the flap remains in firm contact with the stopper, shutting off the flow. Therefore, unidirectional flow can be readily achieved with this in-contact minimized leakage check valve.

Fig. 2 illustrates the operation of the magnetic micropump. It generally consists of two-mode cycles, i.e. priming mode and pumping mode. In priming mode, the device is placed in a magnetic field generated, for example, by an external electromagnet, the magnetic field then produces a magnetic torque on the magnetized permalloy strip, which is directed along the width of the permalloy, and causes the membrane to deflect upward, generating a negative pressure in the pump chamber to open the inlet valve for the fluid to be introduced into the pump chamber, while to shut off the outlet valve to prevent the reverse flow from outlet channel to the pump chamber (Fig. 2a). Next, in the pumping mode, when the external magnetic field is switched off or reversed, the membrane recovers or deflects downward, creating a positive pressure to push the fluid in the pump chamber to the outlet channel. In this case, the outlet valve is under a forward pressure and thus is opened for fluid flow, while the inlet valve is under a reverse pressure and thus checks the reverse flow back to the inlet (Fig. 2b). Hence, by applying a periodic magnetic field, this micropump is capable of producing unidirectional fluid flow continuously.

3. Experiment

3.1. Fabrication process

The fabrication of the micropump device started with the top encapsulation layer using the standard PDMS soft lithography technique [33], in which the SU-8 negative photoresist (SU-8 2100, MicroChem Corp.) was used to fabricate the molding master. Next, for the permalloy electroplated PDMS membrane (Fig. 3), a polyethylene (PE) sheet was first laminated to a 4-in. silicon wafer using double-sided tape. The mixed PDMS prepolymer and curing agent (Sylgard 184 Silicone Elastomer Kit, Dow Corning) at a weight ratio of 1:10 was then spin-coated onto the PE sheet at a speed of 2000 rpm and cured at 70 °C for about 1 h, obtaining an

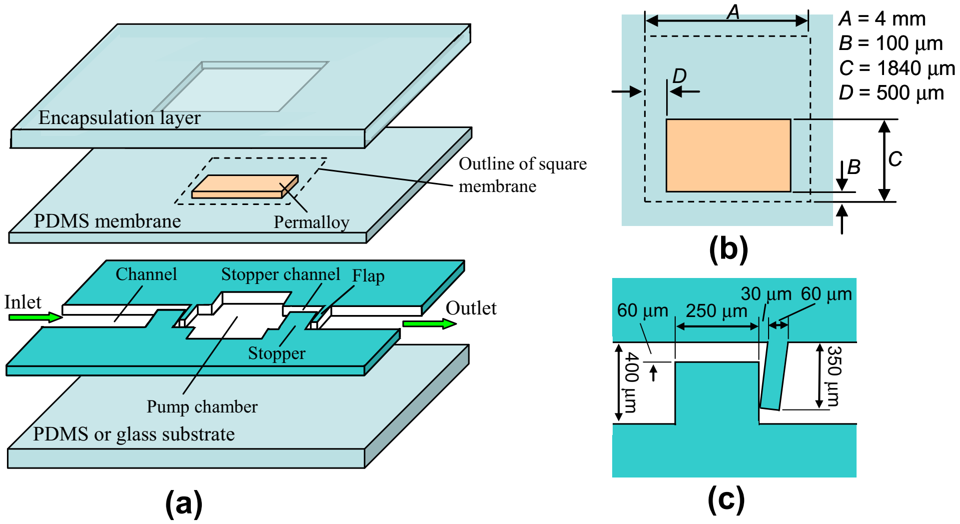

Fig. 1. Schematic of the magnetic micropump design: (a) multilayer structure, (b) layout of permalloy actuator (top view) on a $4 \times 4\ mm^2$ membrane, and (c) detailed design of the check valve (top view).